Thermoresponsive Isopropylacrylamide–Vinylpyrrolidone Copolymer by Radiation Polymerization

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ABSTRACT: In this study, a random copolymer of *N*-isopropylacrylamide and *N*-vinylpyrrolidone [poly(NIPAM-*co*-NVP)] having a thermoresponsive character was prepared by a radiation copolymerization method. Poly(ethylene glycol), PEG 4000, was included in the copolymerization recipe to increase the thermoresponsivity of the resultant copolymeric structures. NIPAM-*co*-NVP copolymers with different thermoresponsive properties were obtained by changing the initial NIPAM/NVP mol ratio, total monomer, and PEG 4000 concentrations. © 1997 John Wiley & Sons, Inc. J Appl Polym Sci **64:** 1775–1784, 1997

Key words: isopropylacrylamide; vinylpyrrolidone; thermoresponsive polymer; radiation polymerization

INTRODUCTION

Thermally reversible hydrogels have recently been of increasing interest in the biomedical field and in biotechnology. Poly(*N*-isopropylacrylamide) [poly(NIPAM)] is one of the most preferred members of this family in these fields. The thermoresponsive behavior of poly(NIPAM) gels was extensively investigated and modeled by different researchers.[1–13] In recent studies, crosslinked poly(NIPAM) and NIPAM copolymers were tried as carrier matrices in the controlled-release applications or in enzyme and cell immobilization studies.[14–17] Park and Hoffman succesfully used poly(*N*-isopropyl acrylamide-*co*-acrylamide) beads in enzyme and cell immobilization studies.[15,16]

Thermosensitive copolymeric structures are usually produced by the copolymerization of a temperature-sensitive monomer with an acrylate-based one. The behavior of thermosensitive poly(acrylamide-*co*-acrylic acid) copolymer gels was explained by hydrogen-bond formation.[18] Amphoteric copolymer gels with different thermoresponsive properties were synthesized by random copolymerization of NIPAM with 3-dimethylaminopropylacrylamide, sodium 2-acrylamide-2-methylpropylsulfonate, and betaine.[19] Temperature-sensitive *N,N*-diethylacrylamide–sodium methacrylate copolymers were obtained as extraction solvents for the biological molecules.[20]

Biological applications usually involve the chemical modification of poly(NIPAM), which can be achieved by random or graft copolymerization of NIPAM with acrylate-based comonomers. Successful chemical modifications usually provide thermoresponsive copolymeric forms of NIPAM including reactive functional groups against biological species. A graft copolymer was prepared by the coupling of poly(acrylic acid-*co*-acrylamide) with poly(NIPAM) and used successfully in the immobilization of lipase by the activation of reactive carboxyl groups on a poly(acrylic acid-*co*-acrylamide) backbone.[21] Thermal and pH-sensitive nanospheres were prepared by the random copolymerization of NIPAM and methacrylic acid

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with an aqueous dispersion polymerization process and used in drug-loading studies.[14]

The form of copolymerization determines the phase-transition behavior of the resultant copolymeric structure against temperature. Chen and Hoffman produced both random and graft copolymers of NIPAM and acrylic acid (AAc).[22] The copolymer was produced by grafting temperature-sensitive oligo(NIPAM) chains onto a pH-sensitive backbone polymer [i.e., poly(AAc)] and exhibited responsive behavior against either temperature or pH changes.[22] In the random copolymerization, a significant loss of thermosensitivity was observed when the AAc component of the copolymer was higher than 10 mol %.[23] In the copolymerization of a thermoresponsive monomer with a nonresponsive one, the critical point is the reflection of thermoresponsive monomer properties into the resultant copolymeric structure. When the nonresponsive comonomer content is high, the random copolymerization of NIPAM with acrylate-based comonomers usually results in copolymeric structures having relatively weak thermosensitivity.

On the other hand, poly(*N*-vinylpyrrolidone) [poly(NVP)] also has thermoresponsive properties and its thermoresponsive behavior is markedly different from that of poly(NIPAM).[24] The lower critical solution temperature behavior for this polymer can be observed at temperatures above the boiling point of water.[24] Poly(NVP) has the ability to bind reversibly to various molecules (dyes, metals, and some polymers) by forming association complexes.[25–28] Therefore, some ligands having interaction abilities with the biological molecules (i.e., dyes or some reactive polymers) may be incorporated more easily into the gel matrix by using the complexing ability of poly(NVP). By introducing an NVP-based structure into a copolymer gel which is thermoresponsive in a proper temperature range, the reversible binding ability of poly(NVP) may be used together with the thermoresponsive behavior to control the interactions of various biological molecules with the derivatized gel matrix.

In this study, a random copolymer of *N*-isopropylacrylamide and *N*-vinylpyrrolidone [poly(NIPAM-*co*-NVP)] having thermoresponsive properties was prepared by a radiation copolymerization method. Poly(ethylene glycol) was included in the copolymerization recipe to increase the thermoresponsivity of the copolymeric structure. Poly(NIPAM-*co*-NVP) copolymers were obtained by changing the initial NIPAM/NVP mol ratio, the total monomer, and PEG 4000 concentrations. Thermoresponsive behavior was obtained for the resultant structures even if the NVP content of the copolymer was kept at a high level.

EXPERIMENTAL

Materials

N-Isopropylacrylamide (NIPAM, Aldrich Chemical Corp., USA) was recrystallized with hexane. The comonomer, 1-vinyl-2-pyrrolidone (NVP, Fluka Chemie AG, Switzerland), was distilled under a vacuum. Distilled water was used in all the copolymerizations. Poly(ethylene glycol) (PEG 4000, M_r: 4000, BDH Chemicals Ltd.) was used as a diluent. The buffer solution for swelling experiments was prepared with potassium hydrogen phosphate ($KHPO_4$, Fluka Chemie AG) and potassium dihydrogen phosphate (KH_2PO_4, Fluka Chemie AG).

Copolymer Preparation

N - Isopropylacrylamide - 1 - vinyl - 2 - pyrrolidone random copolymers were prepared by radiation polymerization. A typical procedure for the copolymerization can be described as follows: NIPAM, 50 mg, and NVP, 50 μL, and PEG 4000, 50 mg, were dissolved in 0.5 mL of distilled water. The glass cylinders 8 mm in internal diameter and 60 mm in length were used as the polymerization reactors. The polymerization medium was purged with nitrogen for 5 min and sealed. The tube was placed in a γ-irradiator (Gammacell 220) and the copolymerization was performed for 72 h at room temperature with a fixed dose rate of 0.5 kGy/h. The dose rate and the polymerization time were determined by the preliminary experiments. The copolymer blocks obtained in the form of short cylinders (8 mm in diameter and 12 mm in length in the synthesis conditions) were collapsed twice at 60°C for 2 h and were washed with distilled water at room temperature for 24 h to remove any unreacted monomers and physically entrapped PEG 4000 within the copolymer matrix.

To compare the thermoresponsive behavior of poly(NIPAM-*co*-NVP) copolymers with the conventional polymer gels, two control gels [poly(NIPAM) and poly(NVP)] were also prepared by the radiation polymerization of corresponding monomers. In this preparation, 50 mg NIPAM or 0.05 mL NVP was dissolved with 0.5 mL of distilled water. The copolymerization medium was purged with nitrogen for 5 min and sealed. The copoly-

Table I Production Conditions of Poly(NIPAM-*co*-NVP) Copolymers; Dose Rate: 0.5 kGy/h, Polymerization Time: 72 h, Room Temperature

NIPAM/NVP Mol Ratio	NIPAM (mg)	VP (μL)	PEG 4000 (mg)	Water (mL)
Effect of total monomer concentration				
48.4/51.6	25	25	—	0.5
48.4/51.6	50	50	—	0.5
48.4/51.6	75	75	—	0.5
Effect of NIPAM/VP mol ratio				
82.4/17.6	50	10	—	0.5
65.2/34.8	50	25	—	0.5
48.4/51.6	50	50	—	0.5
38.5/61.5	50	75	—	0.5
Effect of PEG 4000 concentration				
48.4/51.6	50	50	0	0.5
48.4/51.6	50	50	50	0.5
48.4/51.6	50	50	100	0.5
48.4/51.6	25	25	50	0.5
48.4/51.6	50	50	50	0.5
48.4/51.6	75	75	50	0.5
82.4/17.6	50	10	50	0.5
65.2/34.8	50	25	50	0.5
48.4/51.6	50	50	50	0.5
38.5/61.5	50	75	50	0.5

merization solutions were irradiated with a fixed dose rate of 0.5 kGy/h for 72 h at room temperature. The polymer gels (8 mm in diameter and 11 mm in length in the synthesis conditions) obtained by radiation crosslinking were washed by following the above procedure.

In the copolymer preparation, total monomer concentration, NIPAM/NVP mol ratio, and PEG 4000 concentrations were changed to obtain poly(NIPAM-*co*-NVP) copolymer blocks with different thermoresponsive properties. The conditions for the production of poly(NIPAM-*co*-NVP) copolymers are summarized in Table I. In these conditions, the conversion of monomers was checked by gravimetric determination. In most cases, nearly quantitative conversion values and complete incorporation of NVP into the thermoresponsive gel matrix were achieved.

Thermoresponsivity of NIPAM–NVP Copolymers

To test the thermoresponsivity of copolymers, the equilibrium swelling and the dynamic swelling/deswelling studies were performed in phosphate buffer solution (pH 7.0, total ionic strength: 0.1) with the gels in the form of short cylinders (8 mm in diameter and 11–12 mm in length in the synthesis conditions). These experiments were conducted in a thermostatic water bath (Fryka, Kaltechnik KB 300, Germany) equipped with both cooling and heating systems.

To obtain the variation of equilibrium water content of the gels by the medium temperature, a washed cylindrical copolymer sample prepared in the form of a short cylinder was incubated in 100 mL of the buffer solution at a particular temperature for 24 h. At the end of this period, the weight of the gel sample was recorded after removing the excess surface water with a laboratory tissue. The equilibrium swelling ratio was defined as $(W_e - W_d)/W_d$, where W_e is the weight of the gel after establishment of equilibrium in the buffer solution and W_d is the dry weight of the copolymer sample.

The deswelling kinetics of the copolymer samples was followed by applying a step input on the

medium temperature. The copolymer samples equilibrated in the phosphate buffer solution at +4°C for 48 h were transferred into another phosphate buffer solution at 70°C. The decrease in the water content of the copolymer samples was followed by the determination of the gel weight at designated times. The deswelling ratio is defined as follows:

$$\theta = (W_t - W_d)/[W_{0(+4°C)} - W_d]$$

where θ is the deswelling ratio; W_t, the weight of the gel at a particular time; $W_{0(+4°C)}$, the weight of the gel at equilibrium at +4°C; and W_d, the dry weight of the copolymer sample. A step input on the medium temperature was applied in the opposite direction for monitoring the swelling kinetics of poly(NIPAM-*co*-NVP) gels. For this purpose, the gel samples equilibrated in the phosphate buffer solution at 70°C for 6 h were transferred into another phosphate solution at +4°C. The increase in the water content of the copolymer samples was followed by the determination of the gel weight against time. The swelling ratio is defined as follows:

$$\phi = (W_t - W_d)/[W_{0(70°C)} - W_d]$$

where ϕ is the swelling ratio, and $W_{0(70°C)}$, the gel weight at equilibrium at 70°C. The other symbols are the same as above.

RESULTS AND DISCUSSION

Swelling Behaviors of Poly(NIPAM) and Poly(NVP) Gels

To explain the reason for the use of NIPAM and NVP monomers in the radiation copolymerization, the variation of the equilibrium swelling ratio by the medium temperature was determined for either poly(NIPAM) or poly(NVP) gels. These gels were produced by exposing the corresponding monomer solutions to a fixed dose rate of 0.5 kGy/h at room temperature for 72 h. The crosslinking was achieved only by γ-irradiation and the monomer concentration was fixed to 100 mg/mL in both cases. The effect of temperature on the swelling behavior of the produced gels was studied in phosphate buffer medium (pH 7.0, total ionic strength: 0.1). The variation of the equilibrium swelling ratio by the medium temperature is given in Figure 1 for poly(NIPAM) and poly(NVP) gels. These curves were also used as guidelines for the evaluation of swelling behaviors of poly(NIPAM-*co*-NVP) copolymers. As seen in Figure 1, the equilibrium swelling behavior of poly(NVP) gel against the temperature was markedly different from that of poly(NIPAM). In principle, the thermoresponsive gel matrices having equilibrium swelling behaviors placed between these two curves can be produced by the copolymerization of NIPAM and NVP monomers. In Figure 1, thermoresponsive poly(NIPAM) gel exhibited a sharp transition at 32°C as was expected. Note that the poly(NIPAM) gel by radiation polymerization exhibited a very similar response against the temperature to that of the poly(NIPAM) gels produced by redox polymerization procedures.[29,30] On the other hand, higher swelling ratios relative to those of poly(NIPAM) were observed with the poly(NVP) gel at the studied temperatures. As seen here, poly(NVP) gel was also responsive against the temperature change and the equilibrium swelling ratio of this gel decreased with increasing medium temperature in the range of 4–90°C. But no transition point (i.e., a sudden change in the equilibrium water content by the temperature) was observed with the poly(NVP)

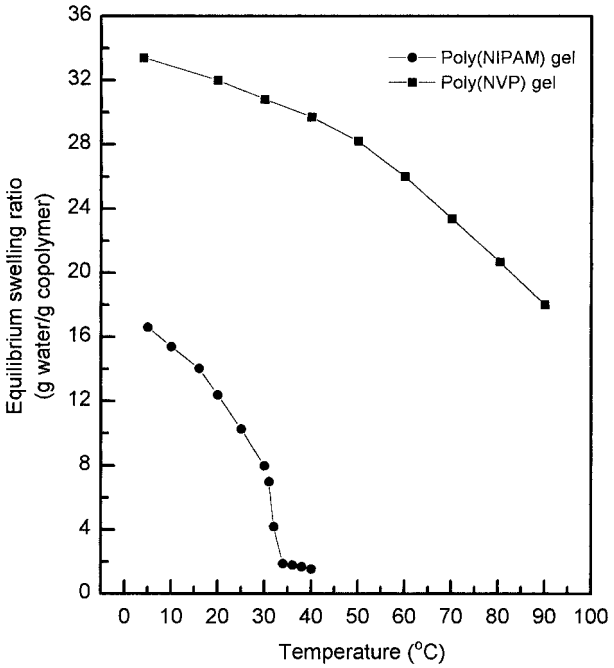

Figure 1 Variation of the equilibrium swelling ratio by temperature for poly(NIPAM) and poly(NVP) gels produced by radiation polymerization, Monomer concentration: 100 mg/mL.

gel in the studied temperature range. Sakellariou reported that the cloud point–polymer volume fraction curve of poly(NVP) represented a typical lower critical solution temperature (LCST) behavior in the temperature range of 140–170°C.[24] The cloud point measurements with the aqueous poly(NVP) solutions also gave theta temperature values above the boiling point of water.[31,32] Therefore, the observed thermoresponsive behavior poly(NVP) gel in Figure 1 was also supported by the related literature. In the light of the findings in Figure 1, it is normally expected that the gel which will be produced by the copolymerization of NIPAM and NVP will possibly have higher equilibrium water contents at low temperatures relative to that of the poly(NIPAM) gel due to its NVP-based structure and will possibly exhibit a sharper equilibrium swelling content change by the temperature relative to poly(NVP) due to its NIPAM-based structure. By considering these properties and the complexing ability of poly(NVP), NVP was selected as a proper comonomer for NIPAM to produce a thermoresponsive gel structure having binding abilities with the various ligands.

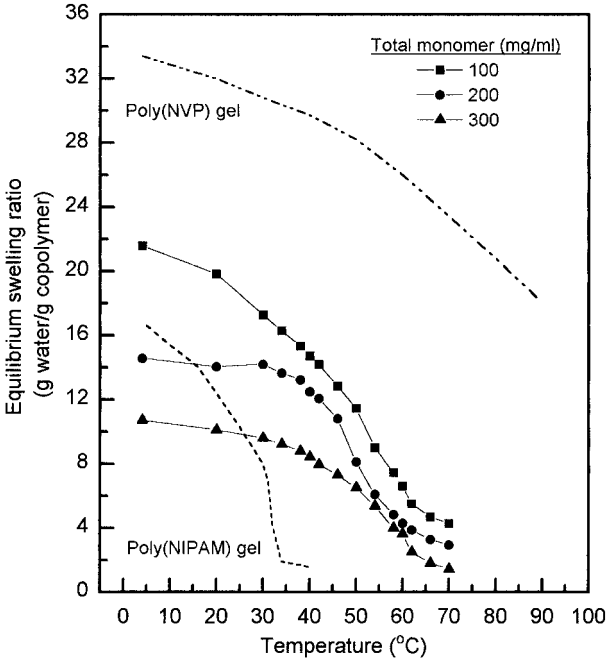

Figure 2 Temperature dependence of equilibrium swelling ratio for the NIPAM–NVP copolymers produced by different total monomer concentrations; NIPAM/NVP mol ratio: 48.4/51.6.

Effect of Total Monomer Concentration

In the copolymerization experiments, the total monomer concentration was changed between 100 and 300 mg/mL by fixing the initial NIPAM/NVP mol ratio to 48.4/51.6. The crosslinking was achieved only by γ-irradiation by exposing the monomer solutions to a fixed dose rate of 0.5 kGy/h at room temperature for 72 h. The variation of the equilibrium swelling ratio of the produced copolymers with the medium temperature is given in Figure 2. The swelling behaviors of poly(NIPAM) and poly(NVP) gels are also included in the same figure. The swelling curve of the copolymer gel produced with the total monomer concentration of 100 mg/mL was placed between the swelling curves of poly(NIPAM) and poly(NVP) gels obtained with the same monomer concentrations. As seen here, the equilibrium swelling ratio of the copolymers decreased significantly after the transition temperature of the poly(NIPAM) gel. The copolymers produced with lower total monomer concentrations exhibited higher thermosensitivity since the equilibrium water content of the copolymer gel at +4°C and the equilibrium swelling ratio difference between +4 and 70°C increased with decreasing total monomer concentration. For the constant gel volume, the decrease in the total monomer concentration causes an increase in the microporosity of the matrix. This case involves an increase in the equilibrium water content of the gel. Therefore, the observed increase in the thermosensitivity of the copolymer gel may be explained by the increase formed in the microporosity of the matrix with the decreasing monomer concentration.

Effect of NIPAM/NVP Mol Ratio

The effect of the NIPAM/NVP mol ratio on the thermoresponsivity of the produced copolymers was studied by changing this ratio between 82.4/17.6 and 38.5/61.5. NIPAM concentration in the polymerization medium was fixed to 100 mg/mL. The temperature dependency of the equilibrium swelling ratio of the copolymers produced with different NIPAM/NVP mol ratios is given in Figure 3. As seen here, higher equilibrium swelling ratios were obtained at constant temperature by increasing the NVP content of the copolymer structure. As was expected, the swelling behaviors of copolymers obtained with higher NIPAM concentrations were more similar to that of the poly(NIPAM) gel and the lower plateau value in the equilibrium swelling curve was obtained at

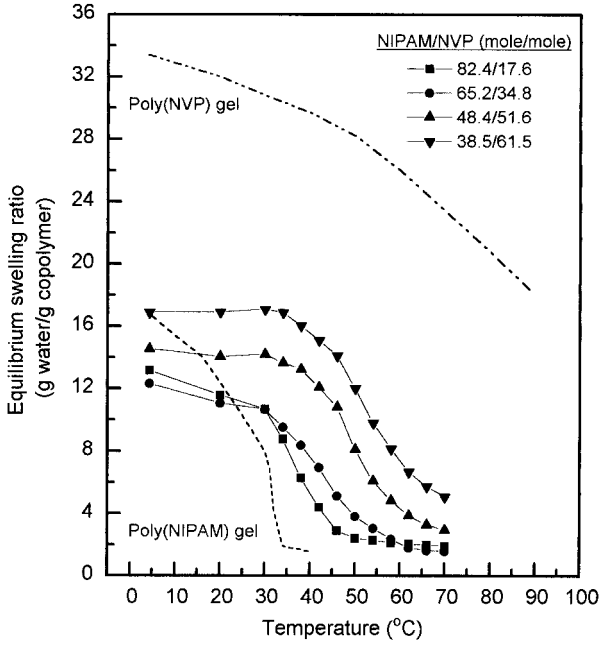

Figure 3 Temperature dependence of equilibrium swelling ratio for the NIPAM–NVP copolymers produced by different NIPAM/NVP mol ratios; NIPAM concentration: 100 mg/mL.

lower temperatures with the gels produced with higher NIPAM contents (i.e., 82.4 mol % NIPAM). But the decrease in the equilibrium swelling ratio was completed at higher temperatures with increasing NVP content (i.e., 61.5 mol % NVP). For copolymer gels, no significant loss of thermosensitivity was observed with increasing NVP content and only the place in the temperature region in which a sharp decrease in the equilibrium swelling ratio was observed, shifted to right by the increasing NVP content of the gel matrix. This behavior is reasonably different from the characteristic behaviors of random copolymers including NIPAM and other acrylate-based monomers.[23] An appreciable thermoresponsive behavior with these copolymers can only be observed up to a limited ratio of acrylate-based comonomer. For instance, in the case of the NIPAM–acrylic acid random copolymer, the transition temperature sharply increases with increasing acrylic acid content and reaches about 70°C at a 20% acrylic acid concentration. Further increase in the acrylic acid content causes a significant loss of thermosensitivity in the copolymer.[23] In our system, the gel structure [i.e., poly(NVP)] obtained by the individual gelation of the comonomer also showed a thermoresponsive behavior. Therefore, no significant loss was observed in the thermosensitivity of NIPAM-containing copolymer gels with increasing comonomer (NVP) concentration.

The dynamic swelling behaviors of poly(NIPAM-*co*-NVP) gels produced with different NIPAM/NVP mol ratios are given in Figure 4. The variation of the dynamic swelling ratio for poly(NIPAM) and poly(NVP) gels was also included in the same figure. As seen here, poly(NIPAM) gel exhibited the highest swelling rate while poly(NVP) had the lowest one. Therefore, the swelling rate of copolymers decreased with increasing NVP content.

To monitorize the shrinking kinetics of the copolymers, the step input on the medium temperature was applied in the reverse direction. The dynamic shrinking behaviors of the poly(NIPAM-*co*-NVP) samples are given in Figure 5. The shrinking curves of poly(NIPAM) and poly(NVP) are also shown in the same figure. As seen here, the fastest shrinking was observed with the poly(NIPAM) gel, which reached the equilibrium state within about 2 h. The time required for equilibrium shrinking significantly increased by the increasing NVP content of the copolymer.

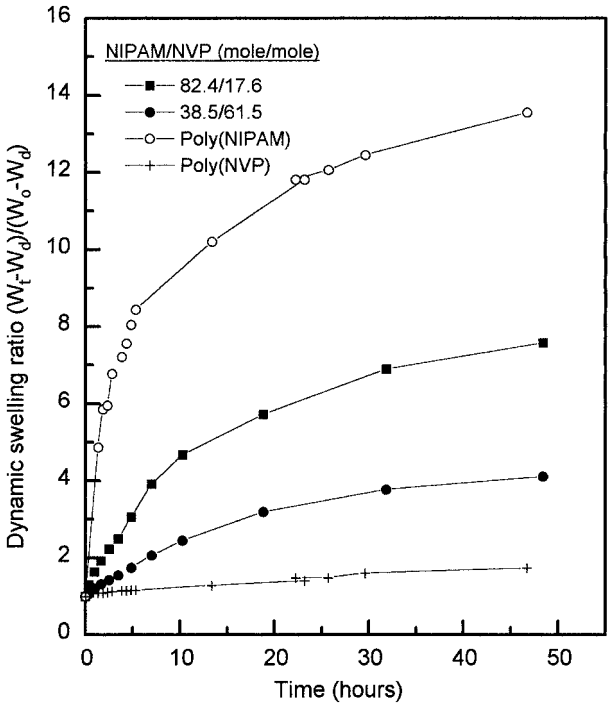

Figure 4 Swelling kinetics of NIPAM–NVP random copolymers produced with different NIPAM/NVP mol ratios. Magnitude of step input for medium temperature: 66°C (from 70 to 4°C); gel properties (after synthesis at room temperature): short cylinders 8 mm in diameter and 11–12 mm in length.

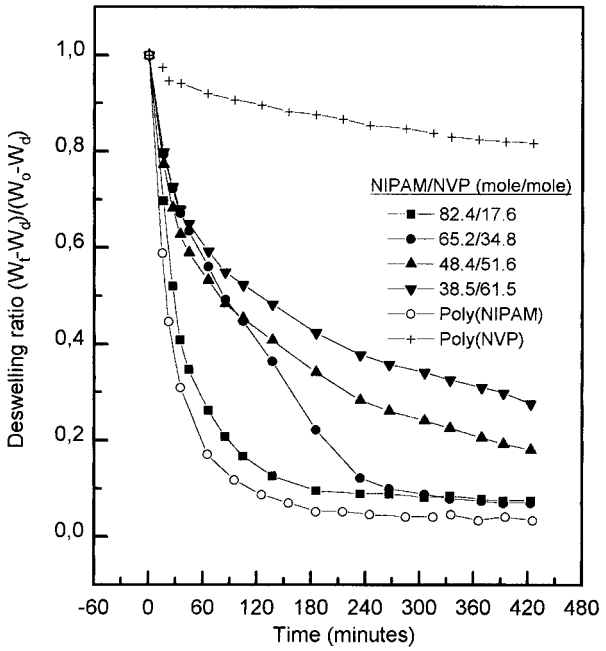

Figure 5 Deswelling kinetics of NIPAM–NVP random copolymers produced with different NIPAM/NVP mol ratios. Magnitude of step input for medium temperature: −66°C (from 4 to 70°C); gel properties (after synthesis at room temperature): short cylinders 8 mm in diameter and 11–12 mm in length.

Effect of PEG 4000 Concentration

To increase the thermoresponsivity of the produced copolymers by creating additional microporosity within the gel matrix, we tried different agents (i.e., some inorganic salts and polymers). PEG 4000 was examined for this purpose since it was soluble in the initial copolymerization medium and its molecular weight was sufficiently low to remove it from the matrix after copolymerization by a diffusion process induced by the shrinking of the gel matrix. The effect of PEG 4000 on the swelling behavior of the poly(NIPAM-*co*-NVP) copolymer at a constant total monomer concentration and at a constant monomer composition was studied by changing the PEG concentration in the gelation medium between 0 and 200 mg/mL. The total monomer concentration and NIPAM/NVP mol ratio were fixed to 200 mg/mL and 48.4/51.6. The variation of the equilibrium swelling ratio of the copolymers produced with different PEG 4000 concentrations is given in Figure 6. The swelling behaviors of poly(NIPAM) and poly(NVP) gels were also included in this figure. As seen here, the use of PEG 4000 caused a significant increase in the thermoresponsivity of the copolymer. The equilibrium swelling ratios at lower temperatures and the difference between the upper and lower plateau regions of the equilibrium swelling curve increased with increasing PEG 4000 concentration. These results may be explained by the formation of additional microporosity within the gel matrix by the increasing PEG 4000 concentration.

As seen in Figure 6, the use of PEG 4000 as a diluent in the copolymerization significantly altered the equilibrium swelling curve of the poly(NIPAM-*co*-NVP) copolymer. To have copolymeric structures having better thermoresponsive properties relative to those produced without using any diluent, the total monomer concentration and NIPAM/NVP mol ratio were changed again by including a constant amount of the diluent (i.e., PEG 4000) in the copolymerization recipe and the copolymer behaviors obtained with PEG 4000 were compared with the those produced in the absence of the diluent.

The effect of monomer concentration on the swelling behavior of copolymers produced in the presence of PEG 4000 is given in Figure 7. In these experiments, the PEG 4000 concentration was fixed to 100 mg/mL and the total monomer

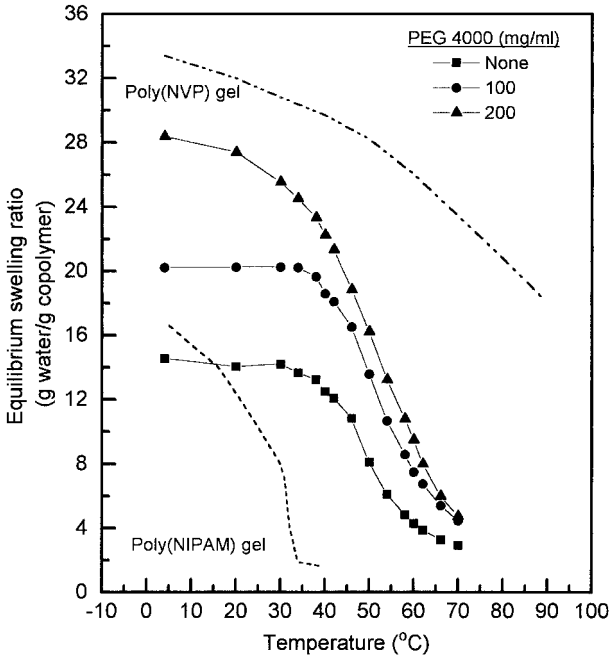

Figure 6 Temperature dependence of equilibrium swelling ratio for the NIPAM–NVP copolymers produced by different PEG 4000 concentrations. Total monomer concentration: 200 mg/mL; NIPAM/NVP mol ratio: 48.4/51.6.

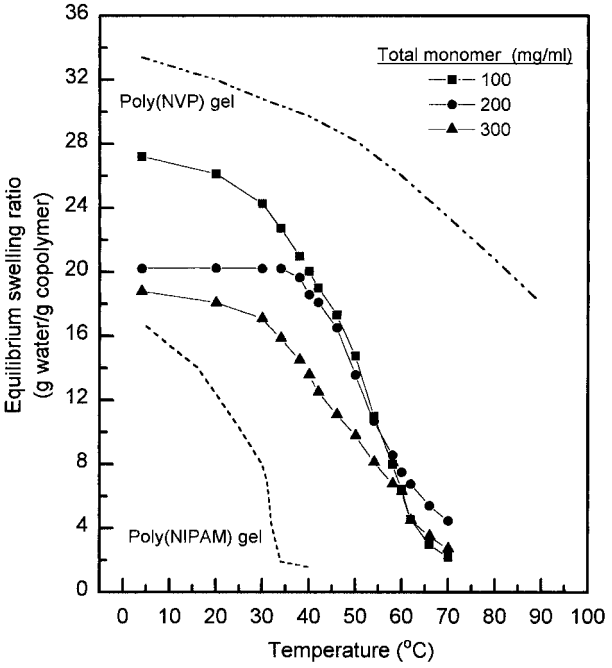

Figure 7 Variation of the equilibrium swelling ratio with the medium temperature for the copolymers produced by changing total monomer concentration in the presence of PEG 4000 as a diluent. NIPAM/NVP mol ratio: 48.4/51.6; PEG 4000 concentration: 100 mg/mL.

concentration was changed between 100 and 300 mg/mL. When the swelling behaviors given in Figure 7 were compared with the results in Figure 2, it was clearly seen that the thermoresponsivity increasing effect of PEG 4000 was valid in all total monomer concentrations. The variation of the equilibrium swelling ratio with the temperature is given in Figure 8 for the copolymers produced by the changing NIPAM/NVP mol ratio in the presence of PEG 4000. Here, NIPAM and PEG 4000 concentrations were fixed to 100 mg/mL. As expected, the equilibrium swelling ratio difference between the upper and lower plateau regions of the curve increased with all NIPAM/NVP ratios in the presence of PEG 4000 relative to those given in Figure 3 sketched for the copolymers produced in the absence of PEG 4000.

To observe the effect of PEG 4000 on the dynamic swelling behavior of poly(NIPAM-*co*-NVP) copolymers, two copolymer gels prepared with different NIPAM/NVP mol ratios (i.e., 82.4/17.6 and 38.5/61.5) were utilized. The variation of the dynamic swelling ratio with the time is given in Figure 9 for the copolymers produced in the presence of PEG 4000. The swelling behaviors of poly(NIPAM) and poly(NVP) gels were also placed in this figure. As seen here, the swelling rate of the copolymer produced with a 82.4/17.6 NIPAM/NVP mol ratio and 100 mg/mL PEG 4000 concentration was very close to that of poly(NIPAM) gel. When the swelling behaviors in Figure 9 were compared with the those obtained for the copolymers produced in the absence of PEG 4000 (Fig. 4), it was seen that the use of PEG 4000 caused a significant increase in the swelling rate of the copolymer produced with the NIPAM/NVP mol ratio of 82.4/17.6. But no significant change was observed in the swelling rate of the copolymer produced with an NIPAM/NVP mol ratio of 38.5/61.5. Therefore, the effect of PEG 4000 on the swelling behavior of the copolymer was strongly related to the copolymer composition. The increase in the swelling rate of the NIPAM-rich matrix may be explained by the formation of additional microporosity by the introduction PEG 4000, which accelerated the water diffusion into the gel matrix. In this copolymer, the dominant part (i.e., NIPAM-based structure) tended to absorb water due to the applied step input. Therefore, an increase in the microporosity of the NIPAM-rich gel caused an appreciable increase in the swelling rate. In the NVP-rich gel matrices, the swelling rate was possibly controlled by the

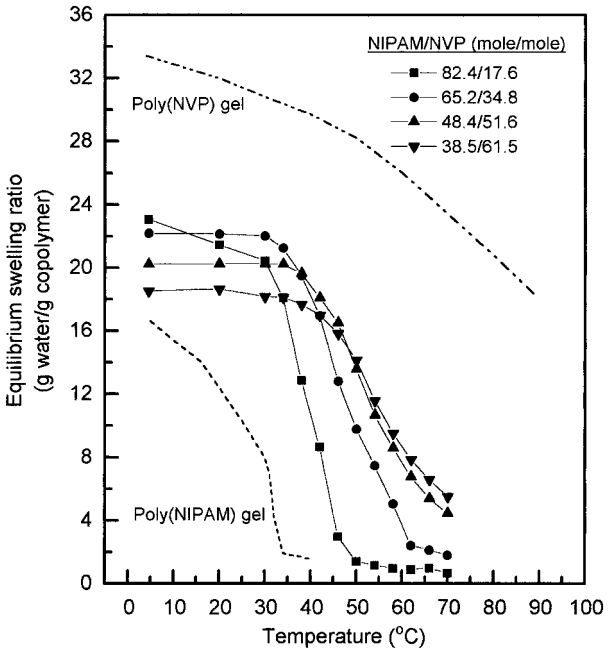

Figure 8 Variation of the equilibrium swelling ratio with the medium temperature for the copolymers produced by changing the NIPAM/NVP mol ratio and in the presence of PEG 4000 as a diluent. PEG 4000 concentration: 100 mg/mL.

NVP part of copolymer. But as seen in Figure 9, the swelling response of the poly(NVP) gel was reasonably lower than that of poly(NIPAM). Due to the dominant limiting effect of the NVP part on the swelling response, the microporosity increase that occurred due to the use of PEG 4000 could not be utilized by the NVP-rich gel matrix for an increase in the swelling rate.

The variation of the deswelling ratio with the time is given in Figure 10 for the copolymers produced in the presence of PEG 4000. In the production of these copolymers, the PEG 4000 concentration was fixed to 100 mg/mL. The comparison of shrinking behaviors in Figure 10 with those observed for the copolymers having the same compositions and produced without using PEG 4000 (Fig. 5) indicated that the shrinking rate of copolymer was not affected by the introduction of PEG 4000 in all studied copolymer compositions. In both cases (i.e., Figs. 5 and 10), the major variable controlling the shrinking rate was the NIPAM content of the gel matrix. On the other hand, the type of porosity is one of the most important

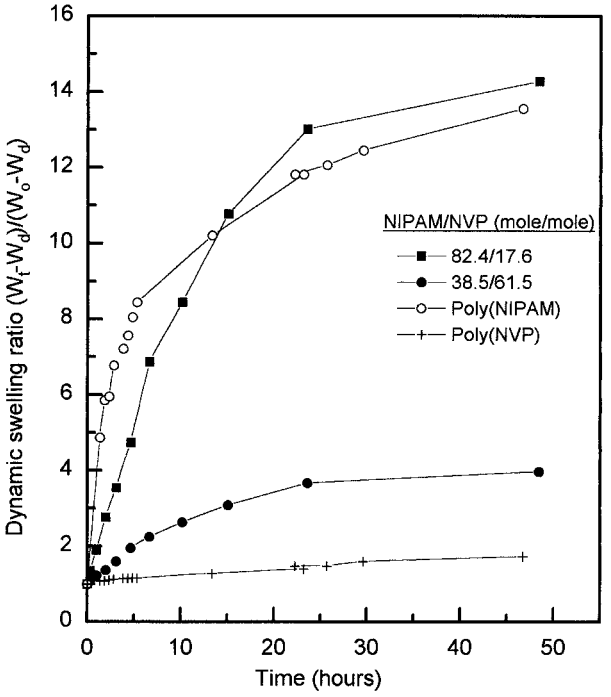

Figure 9 Swelling kinetics of NIPAM–NVP random copolymers produced with different NIPAM/NVP mol ratios in the presence of PEG 4000 as a diluent. Magnitude of step input for medium temperature: 66°C (from 70 to 4°C); gel properties (after synthesis at room temperature): short cylinders 8 mm in diameter and 11–12 mm in length.

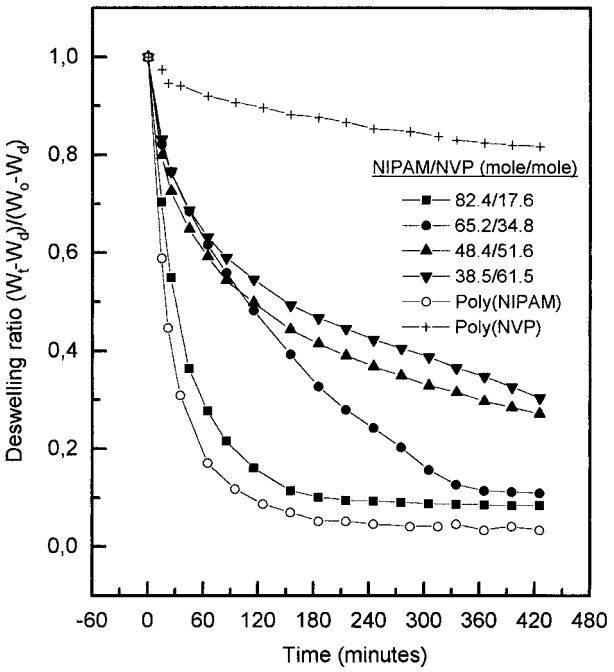

Figure 10 Deswelling kinetics of NIPAM–NVP random copolymers produced with different NIPAM/NVP mol ratios in the presence of PEG 4000 as a diluent. Magnitude of step input for medium temperature: −66°C (from 4 to 70°C); gel properties (after synthesis at room temperature): short cylinders 8 mm in diameter and 11–12 mm in length.

factors for controlling the rate of volume change in thermally reversible gels. The macroporous poly(NIPAM) samples shrunk more rapidly relative to the conventional microporous one and the mass transfer rate of water during the shrinking was reasonably higher than that observed with the poly(NIPAM) samples produced with the conventional recipes since the existence of large pores prevents the skin formation and the large pores cannot close up completely even in the shrunken state.[29] In our results, the shrinking rates of copolymers produced in the absence and presence of PEG 4000 were very close for constant NVP content. In the presence of a microporous structure, the skin formation on the matrix surface cannot be prevented, which determines the deswelling rate in the shrinking process.[29] So, the increase in the microporosity may not be effective on the shrinking rate due to the dominant effect of skin formation. Therefore, the equality of deswelling rates obtained in the absence and in the presence of PEG 4000 also indicated that no significant macropore formation occurred within the copolymer matrix by introducing the diluent into the copolymerization recipe.

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